

THE INFRARED SKY: A SURVEY OF SURVEYS

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ABSTRACT

A subjective review is given of the major milestones in infrared astronomy. Where no direct reference is given I have relied on memory and personal conversations with the people involved. Emphasis is placed on the survey efforts between 2 and 120 μm , the realm of the extrinsic photodetector. The historical developments in infrared astronomy and the pioneering, often marginally successful, survey attempts are put in the perspective of improving technology. Some discussion is given to the survey discoveries and how they have extended our knowledge of the infrared celestial background.

Key words. infrared; astronomy—infrared; surveys

I. Introduction

Technological advances continually produce better instruments and observing techniques for use in astronomy. When these improvements open a new spectral regime to quantitative exploration, the initial efforts usually concentrate on the instrumental performance based on measurements of sources known, or suspected, to be bright. As the technology matures instruments of increasing sensitivity are used for systematic studies to classify the photometric and spectroscopic properties of known sources at the "new" wavelengths. When the technology is sufficiently advanced, large-scale surveys are conducted to catalog the celestial background and to discover the new objects or unexpected properties of known sources that are prominent at the new wavelength.

Of course, the progress is not usually this orderly. Different groups normally work independently in (hopefully) friendly competition to be the "first". Surveys are tried as soon as the observational procedures allow in hope of serendipitous discovery. Throughout it all, the partial successes and downright failures which, at best, become historical footnotes contribute (sometimes significantly) to the technological base which leads to the subsequently acclaimed achievements. This certainly has been the case in infrared astronomy.

Many of the articles published prior to 1960 concentrated on instrumental performance with observations of the brightest objects in the infrared: the planets. The more difficult stellar observations are relatively few up to this time and are discussed in Section II. The rapid improvement in infrared detector technology and observing techniques during the 1960s resulted in a burgeoning number of papers in the literature based on infrared observations; subsequent progress is chronicled in terms of milestones such as photometry at a new wavelength.

The reader is referred to the meticulous compilation of Gezari, Schmitz, and Mead (1987) for more thorough documentation on individual objects. This reference contains an almost complete list of the infrared celestial measurements published by the end of 1986. In the present review, the survey efforts are emphasized by giving details of the unique features of the various instruments as they chronicle the improving sensor technology. Complementary historical reviews may be found in the book by Allen (1975) and the articles by Murray and Westphal (1965) and Sinton (1986).

The significant contributions of the U.S. Department of Defense (DoD), particularly the Air Force, in advancing infrared astronomy in the 1960s and 1970s is placed in perspective; initial ground- and space-based infrared-survey attempts as well as many studies and measurement programs by various university groups were under DoD sponsorship. The DoD interest stems from the fact that passive emission from an object in thermal equilibrium with the near-Earth environment lies almost entirely in the mid-infrared (8–30 μm), a natural consequence of its 250 K–330 K equilibrium temperature. This emission is difficult to suppress and, in most cases, is relatively independent of solar illumination conditions.

II. Historical Perspective

A. Early Developments

Infrared astronomy began with William Herschel's discovery (1800a,b,c,d) and subsequent investigation of the heating effects of invisible solar rays at wavelengths beyond the red. Interestingly enough, Herschel concluded (1800d) that infrared heat from the Sun was fundamentally different than the visible light (Ashbrook 1960; Lovell 1968). Further infrared observations were made on the Sun and Moon in the 1800s but, including E. J. Stone's

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unsuccessful attempt to measure heat from Arcturus in 1870 (Ashbrook 1964). It was over a century after Herschel's studies before the pioneering measurements of stellar infrared emission were obtained by Coblentz (1915, 1922), Abbott (1924), Pettit and Nicholson (1928, 1933), Rust (1938), and Emberson (1941). These early observations relied on the heating of bolometers, radiometers or thermopiles, usually comparing measurements with and without some sort of filter such as glass, mica, or water-absorption cell in the beam. The relatively low sensitivity and slow response time of these devices limited quantitative results but some notable observations were made. Coblentz (1915, 1922) found that, as expected, red stars produce relatively more infrared radiation than blue stars. Abbott (1924) refined these results with wide-bandpass photometry demonstrating a distinct redward shift of the peaks in the spectral-energy distribution for the cooler stars. Pettit and Nicholson (1928, 1933) isolated the infrared emission of 124 stars by differencing measurements made with and without a water-absorption cell in the beam. These heat indices were fundamental to the first comprehensive derivation of stellar effective temperature and bolometric correction scales by Kuiper (1938). Somewhat later, Emberson (1941) expanded the data base with similar measurements on 80 stars.

The next significant development was the use of photodetectors in the late 1940s by Kuiper (1947) and his associates (Kuiper, Wilson, and Cashman 1947). Although the infrared photoresponses of certain materials had been known for sometime, World War II provided the impetus that led the Germans to develop lead sulfide (PbS) from a laboratory curiosity into a usable detector (Kruse, McGlachlin, and McQuistan 1962). Photodetectors are more limited in spectral response than thermal devices but have been developed to the point where they are significantly more sensitive and have much faster response times.

Shortly after the pioneering spectral scans of the Sun, Mercury, and four bright stars by Kuiper and his collaborators, Whitford (1948) used a PbS detector to extend the empirical reddening curve into the near infrared based on stellar photometry in spectral bands of 0.8–1.1 μm and 1.6–2.2 μm . Whitford (1958) later improved the sensitivity of the measurements in his reddening investigation by cooling the cell with dry ice. Felgett (1951) observed 51 stars with a PbS photometer constructed as part of his Ph.D. research. The heat indices he obtained on 28 of these stars by differencing photometry with and without a mica window in the beam agreed well, for the stars in common, with those of Pettit and Nicholson who used a water-absorption cell. Lunel (1960) published the next extensive set of near-infrared stellar photometry. Her observations on 61 stars are notable in that she tried to eliminate atmospheric effects on the photometry by selecting a filter matched to the 2.2- μm atmospheric win-

dow and formally accounting for extinction. V. I. Moroz initiated infrared astronomy in Russia with publications on the 1–5- μm spectra of planets (Moroz 1961b, 1964a), 2- μm photometry of the Crab (Moroz 1960) and Orion nebulae (Moroz 1964b), and an attempt at mapping the galactic center (Moroz 1961a).

B. *The 1960s: Improved Photometry and the First Surveys*

The early investigations were useful but produced few unexpected results. Indeed, the study by Rust (1938) is exceptional in that he tried to characterize very red stars by their infrared properties rather than extending measurements on well-known stars into the infrared. Early design studies by Larmore (1952, 1956), which were extended by Ramsey (1961) and Kauth (1965), used black-body extrapolations of visual observations on known celestial objects to predict the intensities that an infrared detection system would encounter. Walker (1962) generalized this approach to calculate the large-scale distribution of infrared (2.2- μm) radiation on the sky. He first derived stellar visual to infrared color indices as a function of spectral type by assuming the stars radiated like black-bodies with effective temperatures characteristic of the respective spectral types. These indices were then applied to the tabulations of Nort (1950), which divide the Henry Draper Catalog into star counts as functions of magnitude, spectral type, and galactic latitude, to estimate the 2.2- μm diffuse celestial background as a function of galactic latitude. Later, Walker and D'Agati (1964, private communication) used a similar approach for the discrete 2.2- μm background to derive a subset of stars from the Smithsonian Astrophysical Observatory Catalog predicted to be brighter than magnitude +4. This tabulation was useful in identifying sources subsequently detected during near-infrared surveys (Price 1968a, Hughes 1969).

In the late 1950s and early 1960s, the DoD, primarily the Advanced Research Projects Agency (ARPA), sponsored diverse measurement programs to improve the then meager information on the infrared background. For example, Eastman-Kodak/Ohio State University were funded by the Army to obtain stellar photometry with photoconductors at 2.2, 3.8, and 10 μm (Barnhart and Haynie 1964, Barnhart and Mitchell 1966). Lou Meuser, at Wright-Patterson AFB, began a long-term program to develop a 10- μm mapping photometer for use on the 48-inch (1.2-m) Air Force telescope at Cloudcroft, New Mexico—an objective ultimately realized at the ARPA (now Air Force) Maui Optical Station (AMOS) on Mount Haleakala. Russ Walker at the Air Force Cambridge Research Laboratories (AFCL) began a program to characterize the near-infrared sky which included the extrapolative analysis referred to above, as well as near-infrared stellar photometry and a survey. Freeman Hall, at ITT/CR



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Federal Laboratories in California, was contracted to build a satellite tracking radiometer.

The instrument built by Hall in 1960 was capable of scanning over a large area of sky in a relatively short time. A 50-cm Newtonian telescope with a nodding secondary mirror was used to sweep the $1/4^\circ \times 1/4^\circ$ instantaneous field of view of the detector over ± 2.5 . The background emission was suppressed by space filtering; that is, the field of view was rapidly chopped by a spoked reticle, sources smaller than the reticle spacing are modulated while the general background remains constant. Synchronous rectification was used to detect the sources while eliminating the background. Low-level signals were detected by their ordered appearance on repeated scan lines on a memory oscilloscope. Hall and Stanley (1962) made the first measurement of a satellite (1959 *Echo I*) longward of $3\ \mu\text{m}$ with this instrument. Hall also obtained $1\text{--}3\ \mu\text{m}$ photometry on 40 stars and four planets. He found that the stellar $1\text{--}3\ \mu\text{m}$ magnitudes were consistently brighter, by as much as a factor of 2 to 4 for late-type stars, than those predicted from blackbody extrapolations of visual magnitudes and effective temperatures of the corresponding spectral types. Thus, Hall (1961) recognized relatively early that "stars cannot be regarded as radiating like blackbodies with a temperature estimated from their visual appearance", a conclusion concurrently reached by the Eastman Kodak/OSU group (Augason and Spirad 1965).

Hall (1964) used the ITT instrument, which was tailor-made for scanning large areas, to conduct the first successful near-infrared survey of the sky during the summer months of 1962. A total of 18% of the sky was surveyed with a PbS cell cooled with dry ice. About 50 stars were detected with $1\text{--}3\ \mu\text{m}$ magnitudes brighter than about $+1.0$ along with a number of marginal detections and/or indications of possible clustering and extended emission. Hall also tried smaller area coverage at $5\ \mu\text{m}$ with a Telluride (Te) detector and at $10\ \mu\text{m}$ with a Mercury-doped Germanium (Ge:Hg) photoconductor; positive detections were obtained at $10\ \mu\text{m}$ only on Venus and Mars. A concurrent $2.2\text{--}\mu\text{m}$ survey by Walker (Augason and Spirad 1965) using a nitrogen-cooled PbS photometer and a 20-inch (50-cm) telescope was not as productive.

The rapid development of near-infrared stellar photometry in the early 1960s can be attributed, in large part, to the efforts of H. L. Johnson and his collaborators at the University of Arizona. In the 1950s this group began an extensive-measurements program to obtain accurate and systematic photometry of the brightest stars. This photometry was extended to the atmospheric windows centered 1.2 , 2.2 , and $3.4\ \mu\text{m}$ (Johnson 1962; Johnson *et al.* 1966) as the appropriate instrumentation was developed. These observations formed the data base upon which Johnson revised the effective temperature and bolometric correction scales for the brightest stars (Johnson 1964),

carbon stars (Mendoza and Johnson 1965), and M dwarfs (Johnson 1965b). The review of Johnson (1966a) coordinates the results of these studies into a single set of reference tables. Thus, the discrepancies noted by Hall were systematically addressed.

In 1963–64, Hall constructed a more sensitive all-aluminum infrared survey telescope capable of detecting both point and extended sources. The 60-cm, $f/2$ primary was patterned after the 60-inch (1.5-m) aluminum mirror which had been designed by the University of Arizona for infrared photometry (Johnson 1966b). A linear array of 30 PbS detectors, each with a one square-arc-minute field of view, was mounted on a two-stage thermoelectric cooler at the Newtonian focus behind an eight-bladed opaque chopper. The average sensitivity of the instrument was about $2 \times 10^{-15}\ \text{W cm}^{-2}\ \mu\text{m}^{-1}$ resulting in a detection level (signal-to-noise ratio of 3) equivalent to a magnitude of $+2$ at $2.2\ \mu\text{m}$. Surveying with this instrument began in the summer of 1965, about the time that the Cal Tech group announced preliminary results of a more sensitive survey (Neugebauer, Martz, and Leighton 1965). Rather than compete with this effort, Hall decided that the ITT instrument would be more productive in the Southern Hemisphere providing complimentary coverage. A survey of the southern sky began in February 1967 under AFCRL sponsorship but unusually poor weather that year limited the number of relatively clear nights to an average of only two per week. Consequently, the results were too meager and progress too slow for AFCRL to continue funding and the effort was terminated in September 1967.

Price (1968a) published the survey detections as a list of 414 sources in 2000 square degrees south of -30° declination. About 15% of the sources in the list were associated with cool, late-type variable stars. The relative proportion of these variable stars increases at the fainter visual magnitudes becoming the majority for stars with $m_v > 8.5$. Price (1968c) also found that the infrared index ($m_1 - m_{2.2\ \mu\text{m}}$) for Mira variables increases with period and the indices for irregular variables are, generally, larger than those of the Mira and semiregular variables. Subsequent analysis by DeGioia-Eastwood *et al.* (1981) at longer wavelengths confirmed the correlation of infrared excess with period for Miras. Finally, one of Freeman Hall's original survey objectives was realized with the discovery (Price 1968a,b) of an extended ($2' \times 4'$) infrared source, a heavily obscured open cluster in Ara (Westerlund 1968).

To date, the most comprehensive near-infrared survey is the "Two Micron Sky Survey" (designated hereafter as the TMSS) of Neugebauer and Leighton (1968, 1969). The instrument was quite innovative; the 157.5-cm primary was made by allowing epoxy to solidify on a rotating aluminum frame spun at a rate sufficient to produce an $f/1$ surface, then aluminizing the resulting optical element. The focal-plane array of four pairs of PbS detectors and a single Si cell was located at the prime focus and cooled

with liquid nitrogen. The PbS detectors, each subtending a $3' \times 10'$ field of view, were filtered for a spectral bandpass of 2.0 to 2.4 μm (equivalent to the Johnson K band) while the $3' \times 30'$ silicon element was filtered to respond in the region from 0.7 to 0.9 μm (the I band). The primary was wobbled at 20 Hz to sweep the field of view back and forth across a pair of adjacent detectors and the resulting signals differenced to reduce the background.

The region between $-33^\circ < \delta < 82^\circ$ was surveyed at least twice with approximately 2×10^4 sources observed above the minimum detectable intensity of $10^{-15} \text{ W cm}^{-2} \mu\text{m}^{-1}$ (Hughes 1969). The TMSS catalog contains the brightest 5612 of these sources, all of which had been measured at some time to be 2.5 times above the minimum level (equivalent to a 2.2 μm magnitude of +3).

The performance of the TMSS instrument was quite remarkable. An unpublished extension of the survey (Neugebauer 1971, private communication) covers the declinations between -33° and -46° ; the most southerly declination is only 10° above the horizon at the observing site on Mount Wilson. Thus, these observations were made through 2.5 to 6 air masses resulting in 25% to 50% atmospheric extinction at 2.2 μm . Even at these large extinctions, the Cal Tech instrument was about 4 times more sensitive than the ITT survey telescope.

The TMSS catalog defines a near-infrared sky dominated by cool, red stars: M, S, or C stars with $T_e \leq 4000 \text{ K}$ constitute 70% of the catalog according to the compilation of Bidelman (1980). The mode in the distribution of stellar spectral types is at M5 with half the total number of stars in the catalog within two spectral subdivisions of this. By contrast, the tabulations by Nort (1950) indicate less than 3% of the stars in the Henry Draper Catalog with $m_i \leq 5.5$ are this cool. The $(I-K)$ color indices of the reddest stars in the TMSS catalog are much larger than can be accounted for by the effective temperature and molecular line blanketing. Among this group of stars are highly reddened supergiants (Kleinmann and Payne-Gaposchkin 1979; Grasdalén and Sneden 1979), characterized by their nonvariability and concentration to the galactic plane, and a new class of large-scale contributors to the celestial background: stars (usually giant variable stars of late spectral type) embedded in circumstellar dust shells. The large color indices for these objects result from reddening by the surrounding dust shell. From the association of maser emission with circumstellar dust shells and the color characteristics of these objects, Kleinmann *et al.* (1979) estimate it is likely that the large majority of the sources in the TMSS with $(I-K) > 3.6$ ($\sim 40\%$ of the catalog) fall into this category.

As a large-scale unbiased survey of late-type stars the TMSS provides a unique data base to study their intrinsic properties since visual studies of these stars are usually limited to a small portion of the sky, are biased by interstellar extinction effects, and are difficult to interpret due

to the very small number of such stars in the solar vicinity. Hughes (1969) and Mikami and Ishida (1981) analyzed the galactic properties of the stars in the TMSS by sampling according to the $(I-K)$ index. Both analyses assume a functional form for the vertical scale height and a normal (Gaussian) luminosity distribution for each $(I-K)$ sample. Hughes (1969) derives absolute K magnitudes, the luminosity dispersion, the number densities at the Sun, and scale heights for each subclass. Mikami and Ishida (1981) assume the values for the absolute K magnitude and luminosity dispersion for each subgroup and derive the number densities in the solar vicinity and the scale heights. The analyses confirm that, except for the supergiants, the TMSS M giants lie well within a kiloparsec of the solar neighborhood, have a vertical scale height of 300–400 pc, and have a density in the solar neighborhood of several times 10^{-3} kpc^{-3} .

The Valinhos survey is the only extensive near-infrared Southern Hemisphere survey to date with published results at a sensitivity comparable to the TMSS. The area between 240° to 360° longitude within 5° of the galactic plane was surveyed at 2.2 μm with a single detector at the Cassegrain focus of the 60-cm telescope at the de Moraes Observatory of the University of Sao Paulo in Brazil. Epchtein *et al.* (1985, 1987) published follow-up infrared photometry on 630 sources selected from the more than 1500 detections with $K \leq 5.5$. Unfortunately, a catalog of all the sources has not been released.

Fainter surveys have been limited to small-area investigations of the structure of the galaxy or star-forming regions. K -band measurements are useful probes for the stellar content in heavily obscured regions as the extinction at 2.2 μm is only a tenth that in the visual and the thermal emission from circumstellar dust shells is relatively small at this wavelength. On the large scale, the near-infrared sources in the direction of the north galactic pole tend to be bluer at the faint magnitudes, the dominant spectral type at a given magnitude shift from late K and M giants to G dwarfs (Elias 1976). This implies that away from the galactic plane the majority of the late-type giant stars are included in the TMSS and that applying the proper $(V-K)$ index to the local luminosity function will predict the near-infrared background at fainter levels. In the plane, structure has been probed with selected area deep surveys by Kawara *et al.* (1981, $K < 6.8$), Eaton, Adams, and Giles (1984, $K < 10.5$), Jones *et al.* (1981, $K < 10.5$), Jones *et al.* (1984, $K < 9.5$). The aggregate sampling covers longitudes between 320° through the galactic center out to 60° . These investigations show that more luminous stars (OBs and supergiants) are required than are predicted by extrapolating the local visual luminosity function (Jones *et al.* 1981; Eaton, Adams, and Giles 1984) in order to account for the observed source densities. The scale length of the disk in the near infrared is small, 2–2.5 kpc. This is compared to 3.5 kpc found from H I observa-

tions (Gunn, Knapp, and Tremaine 1979) and ≥ 2.5 kpc for the visible disk from an analysis of a smaller number of relatively low-latitude fields by Bahcall and Soneira (1984).

Lebofsky and Rieke are currently engaged in an ambitious effort to survey 15 square degrees of the sky at 2.2 μm to 17th magnitude. This study uses a 32×32 HgCdTe array at the focus of the 1.8-m University of Arizona CCD Transit Instrument (McGraw *et al.* 1984). These data should provide valuable information on galaxies at high redshift and constrain the low-mass end of the local luminosity function.

C. Mid-Infrared Photometry

During the mid-1960s several groups were actively engaged in extending astronomical measurements to longer wavelengths. The Golay cells used by Sinton and Strong (1960a,b) to obtain 8–13 μm spectrometry and photometry of Mars and Venus were supplanted by the much more sensitive doped germanium photoconductors (Willey and Murray 1964a) and the germanium bolometer (Low 1961). The early mid-infrared measurements proved to be difficult since the thermal emission from the telescope and the atmosphere provide a background which severely limits the sensitivity of photometric observations. The photon background can be reduced by careful design of the telescope and dewar, leaving the far more serious problem of the spatial and temporal variations in the atmospheric emission. This "sky noise" seriously degraded the early survey attempts of Hall (1964) and produced erroneous indications of clustering and extended emission in his 1–3 μm survey.

Sky noise is reduced by using a small field of view and beam switching, that is, alternately viewing adjacent fields, one containing the source of interest and the other empty sky. Synchronous rectification of the signal cancels the emission common to both beams; the closer the two fields are the greater the correlation in the emission and the higher the cancellation in sky noise. Johnson (1962) and Johnson and Mitchell (1963) used these techniques to extend stellar photometry to 5 μm . Successful 10- μm photometry was initiated at Cal Tech (Murray and Willey 1963, Willey and Murray 1964a,b) and at the University of Arizona (Low and Johnson 1964). Photometry in the atmospheric windows at 20 μm (Johnson, Low, and Steinmetz 1965; Low 1966) and 34 μm (Low, Rieke, and Armstrong 1973) followed in due course.

Using a small field of view would obviously make a large-area survey from the ground prohibitively time consuming and beam switching discriminates against extended sources. This was clearly demonstrated by the two ground-based survey attempts at $\lambda > 4$ μm . A 5- μm survey with the TMSS telescope was seriously degraded with a cell-noise-limited performance of $m(5 \mu\text{m}) \leq -1.5$ mag being achieved only 3% of the time during a year of

observing (Neugebauer 1973). Concurrently, Frank Low (1973; also Low *et al.* 1976) attempted surveys at 5 and 10 μm after spending two years developing an optimal ground-based survey instrument. The greatest 5- μm sensitivity over the approximately 700 square degrees surveyed was $5 \times 10^{-15} \text{ W cm}^{-2} \mu\text{m}^{-1}$, equivalent to the best achieved by Neugebauer. Low also surveyed about 1000 square degrees at 10 μm in a one-year period reaching a minimum detectable flux of $3.5 \times 10^{-16} \text{ W cm}^{-2} \mu\text{m}^{-1}$ about 25% of the time. Only one source, AFGL 490, was subsequently confirmed out of a possible 44 detections. To give proper credit to Low's efforts, it should be noted that the detection of AFGL 490 was independent of and contemporaneous with the AFCRL rocket-survey discovery. Even with the recent improvements in telescope design and the automated observing procedures, atmospheric limitations still make a comprehensive ground-based survey beyond 4 μm impractical.

D. Aircraft Platforms

The atmospheric emission above the 10- and 40-km altitudes reached by aircraft and balloons, respectively, is lower by a factor of 10^2 and 10^3 compared to that encountered by ground observatories. The molecular absorptions which restrict ground-based measurement to infrared atmospheric windows are significantly reduced and observations in the opaque regions are feasible. This is particularly important for the spectral region from 35 μm to the submillimeter.

The initial infrared astronomical measurements from an aircraft platform during the mid- to late-1960s are described by Low, Aumann, and Gillespie (1970). Photometric observations of Jupiter and Saturn (Aumann, Gillespie, and Low 1970), the galactic center (Aumann and Low 1970), and H II regions (Low and Aumann 1970; Harper and Low 1971) were obtained with a small telescope flown on a modified Lear Jet, in part with financial support from AFCRL. NASA augmented the Lear jet in the mid-1970s with the Kuiper Airborne Observatory (Bader and Wagoner 1970; Bader and Witteborne 1972; Cameron and Strane 1974; Cameron 1976), a passively cooled 91-cm diameter telescope on a C-141 aircraft. Chopping with small fields of view is still required to reduce the sky noise and thermal emission from the residual atmosphere above the aircraft. Consequently, the aircraft-based telescopes have primarily been used for photometry and very limited area mapping centered on specific sources.

E. Balloon Platforms

The higher altitude and extended float times on balloons permit long integration and larger areas of sky to be surveyed. The first extensive balloon-based program was at John Hopkins with an initial flight in November 1959. This experiment was inconclusive but Bottema, Plummer, and Strong (1964) subsequently reported spectral

measurements on Venus at 1.13 μm during a February 1964 flight. Project Stratoscope at Princeton University obtained 1–7.5- μm spectra of Mars on a March 1963 flight (Danielson *et al.* 1964) and 1–3- μm spectra of red-giant and supergiant stars (Woolf, Schwarzschild, and Rose 1964; Danielson, Woolf, and Gaustad 1965), Jupiter (Danielson 1966), and the Moon (Watson and Danielson 1965) on a November 1963 experiment. These balloon-based measurements were above much of the atmospheric water vapor and were affected significantly less by atmospheric CO_2 , CO, and H_2O than the ground-based infrared stellar and planetary spectral measurements by Kuiper *et al.* (1947), Kuiper (1947, 1963, 1964), and Moroz (1961a, 1964b). However, even at balloon altitudes the 5–30- μm spectral region is usually avoided since the ambient atmospheric emission peaks in this spectral region. Notable exceptions to this were the AFCRL balloon flights in April 1971 by Logan, Balsamo, and Hunt (1973) to measure the 10–12.5- μm Martian radiance profiles and in 1974 to measure the absolute spectral radiance of Venus and Jupiter between 4.5 and 16 μm (Logan *et al.* 1974). Of historical note is that the 60-cm primary optical system flown by the AFCRL group on the 1971 experiment was made entirely of beryllium, the largest set of such optics flown for infrared astronomical measurements until the *Infrared Astronomical Satellite* (IRAS).

A detection of the Moon at 100 μm by Hoffman *et al.* (1967) was the first balloon-based observation at longer wavelengths. This was followed by 100- μm photometry of the galactic center (Hoffmann and Frederick 1969), a subsequent more-detailed map of the galactic center (Hoffmann, Frederic, and Emery 1971a), and a survey along the galactic plane (Hoffmann, Frederick, and Emery 1971b) which covered about 750 square degrees in a single spectral band spanning the 80–135- μm region. Friedlander and Joseph (1970) and Friedlander, Goebel, and Joseph (1974) attempted a larger area survey in a very broad spectral band (40–250 μm) with limited success.

Approximately 270 square degrees of sky were scanned on two balloon flights in September 1971 in a broad (40–350 μm) spectral band by Furniss, Jennings, and Moorwood (1972). Several objects were detected including two unidentified sources. Subsequent flights by this group with modification of the balloon instrument produced 40–350- μm maps of NGC 6357 and NGC 6334 (Emerson, Jennings, and Moorwood 1973), the galactic center and W51 (Alvarez *et al.* 1974), W3 (Furniss, Jennings, and Moorwood 1974, 1975) as well as far-infrared photometry on a number of H II regions.

The balloon experiments active during the early 1970s are reviewed by Hoffmann (1977) while Drapatz (1982) described more-recent instrumentation. Subsequent balloon-borne infrared astronomy has developed in two main directions: (a) large-scale surveys with relatively small telescopes and large fields of view; and (b) observatory-

type far-infrared measurements taken with large telescopes and diffraction-limited fields of view. The balloon-borne surveys can also be divided into two main categories: the near infrared, primarily at 2.4 μm with some 3.5- μm measurements, and the far infrared at $\lambda > 50 \mu\text{m}$.

The near-infrared measurements are made in the narrow spectral gap ($< 0.1 \mu\text{m}$) at 2.4 μm between the $\Delta v = 1$ and 2 bands of OH to avoid the rapidly varying background produced by this molecule above balloon altitudes (Sugiyama, Maihara, and Okuda 1973). Large instantaneous fields of view, 1° – 2° , were used in the early experiments to compensate for the narrow spectral bandwidth and small size (10–20-cm) of the telescopes. Hofmann *et al.* (1973) detected the large-scale 2.4- μm zodiacal emission at an elongation of about 24° . Diffuse 2.4- μm emission has also been mapped along the galactic plane between $-70^\circ < \ell < 65^\circ$ (Maihara *et al.* 1978; Hayakawa *et al.* 1981). Measurements at 3.4 μm by Hofmann, Lemke, and Thum (1977) and Hayakawa *et al.* (1981) are inconsistent and may not be well calibrated.

The galactic plane has also been surveyed at longer wavelengths in various spectral bands between 50 and 300 μm (Low *et al.* 1977; Maihara, Oda, and Okuda 1979; Nishimura, Low, and Kurtz 1980; Gispert, Puget, and Serra 1982; Caux *et al.* 1984, 1985). These surveys were made with modest-sized telescopes (< 20 -cm diameter) and large fields of view ($0^\circ 25'$ – 1°). The most extensive coverage is by Caux *et al.* (1984, 1985) producing 71–95- μm and 114–196- μm maps between $270^\circ < \ell < 110^\circ$. Okuda (1981) summarized the large-scale surveys active during the 1970s and includes many of the early balloon-borne investigations not referenced here.

The balloon observations clearly show the large-scale, edge-on view of our galaxy. The 2.4- μm measurements limit the stellar content while the far-infrared measurements highlight the H II regions. A roughly constant ridge of emission underlies a number of discrete extended sources along the galactic plane between $330^\circ < \ell < 30^\circ$, the emission then decreases almost exponentially with increasing longitude from the center. The emission ridge within 30° of the galactic center has an observed half-width at full maximum of 3.5 to 5° at 2.4 μm (Maihara *et al.* 1978; Hayakawa *et al.* 1981; Melnick *et al.* 1987; Koch *et al.* 1987a), 2.5° at 4.2 μm (Price 1981), and narrows to about 1° in the far infrared. A spheroidal bulge at near-infrared wavelengths ($\lambda \leq 5 \mu\text{m}$) surrounds the galactic center out to about 10° ; the near-infrared colors of this component are entirely consistent with emission from late-type giants if reasonable interstellar reddening is assumed (Little and Price 1985).

The near-infrared emission has been effectively modeled with an ellipsoidal bulge, a galactic disk plus rings or arms, and extinction estimates from reasonable assumptions for the interstellar dust distribution (Hayakawa *et al.* 1977; Maihara *et al.* 1978; Oda 1985). The disk scale

length in these models, 2–2.5 kpc, agrees with the value derived from source counts. These models also require a region of enhanced luminosity, assumed to be due to supergiant and giant stars, in a narrow ring of 50 pc vertical scale height at 4–5 kpc from the galactic center to account for the emission ridge.

Smaller areas have been surveyed at improved resolution. The Cygnus X region (Campbell *et al.* 1980) and the galactic plane between 11.5 and 17° longitude (Campbell *et al.* 1984) were mapped at 100 μm with 0.2 resolution. Jaffe, Stier, and Fazio (1982) surveyed a 7.5-square-degree section of the galactic plane and Odenwald and Fazio (1984) covered 8.5 square degrees around the galactic center with a 1-m telescope at 1' resolution. The small field and beam throw used on this instrument may have filtered the large extended component of the background emission as there is a factor of 3–4 discrepancy for some of the sources in common with Campbell *et al.* (1984).

III. Probe-Borne Infrared Surveys

A. The Early Sounding Rocket Experiments

Flying the telescope into space eliminates the problems associated with atmospheric emission and absorption. Furthermore, the sensor can be cooled in the vacuum of space to temperatures where the instrumental background no longer limits the detector performance, even for large fields of view. The rapid response times and high sensitivities of photoconductors under low background conditions made it possible to collect a significant amount of data in the 200 to 300 seconds of flight time above the atmosphere provided by the early sounding rockets.

In the summer of 1962, the NASA Astronomy Subcommittee appointed a panel to determine the status of infrared astronomy and provide a background to assist the committee in assessing possible space applications to the field (Augason and Spinrad 1965). A 1964 poll of the infrared astronomy community was taken by NASA as to what direction space-based applications the field should take. The majority opinion was that resources should first go into realizing the large potential increase in sensitivity for ground- and aircraft-based photometry through careful instrument design and improved observing procedures. Some flavor for these issues may be found in the discussion which follows the article by Harwit *et al.* (1966). However, following its charter to promote use of space, NASA sponsored the Naval Research Laboratory (NRL) and Cornell University to fly the first infrared astronomical experiment on a sounding rocket. A 14-cm, $f/0.8$, liquid-nitrogen-cooled telescope was launched from White Sands Missile Range, New Mexico (WSMR) on 1965 October 29 but failed to detect any signals (Harwit *et al.* 1966). Both groups subsequently developed and independently flew liquid-helium-cooled instruments. The Cornell telescope employed an 18-cm $f/0.9$ primary

with four $5^\circ \times 5^\circ$ detectors at the prime focus to cover the spectral range from 5 μm to 1.3 mm (Harwit, Houck, and Fuhrman 1969). An elevated submillimeter background was detected with this instrument on a February 1968 flight (Shivanandan, Houck, and Harwit 1968), a result confirmed on a reflight later that year (Houck and Harwit 1969). Although these experiments concentrated on the diffuse cosmic background, Feldmann, McNutt, and Shivanandan (1968) did detect discrete sources in the direction of Ursa Major, probably the ejected nose cone.

The Cornell University group continued to fly rocket-borne experiments, in part with AFCRL funding, through the mid-1970s obtaining 5–6- μm , 12–14- μm , and 85–114- μm measurements of the galactic center (Houck *et al.* 1971; Soifer and Houck 1973) and H II regions along the galactic plane (Soifer, Pipher, and Houck 1971) with $1/4^\circ \times 1^\circ$ detectors. The thermal infrared emission from the zodiacal dust was detected on a single plane crossing during a 1970 flight at large solar elongation ($\sim 100^\circ$) by Soifer, Houck, and Harwit (1971). A subsequent 1974 experiment obtained a single 8–14- μm spectrum of the zodiacal emission, also at large elongation (Briotta, Pipher, and Houck 1976; Briotta 1977).

At shorter wavelengths, the near-infrared zodiacal emission at an elongation of about 23° was measured on a rocket-borne experiment by Hayakawa, Matsumoto, and Nishimura (1970) in spectral bands centered at 1.57 and 2.16 μm . Near-infrared measurements are important in understanding the physical properties of the zodiacal dust since this spectral region spans the crossover from reflected sunlight to thermal emission. Matsumoto, Akiba, and Murakami (1987) recently reported rocket-borne observations of this spectral crossover for the zodiacal dust cloud out of the ecliptic plane and at large elongations. This experiment was a significant improvement over an earlier one which observed an anomalously large background attributed to extragalactic sources (Matsumoto, Akiba, and Murakami 1984). Other near-infrared rocket-based survey measurements are those of Hayakawa *et al.* (1978) and Noguchi *et al.* (1981) along the galactic plane at 2, 2.8, and 4.5 μm .

B. The Air Force Surveys

These experiments, as well as the balloon-based surveys, sample the celestial background by concentrating on the galactic plane and regions known to be bright in the infrared. In the late 1960s the DoD became actively interested in characterizing the general mid-infrared background by means of a large-scale unbiased survey. The ground-based efforts by Neugebauer and Low at $\lambda > 4 \mu\text{m}$ were funded as part of this effort, but a rocket-borne survey was seen as the next step. Based on their previous experience, NRL was the logical choice to perform the rocket survey. NRL was, however, deeply involved in the far-infrared experiments and lacked the facilities to handle both programs. The task fell to AFCRL.

In 1970 AFCRL flew two proof-of-concept experiments using a small (10-cm) liquid-neon-cooled telescope with a linear array of six $10' \times 10'$ detectors filtered for a 12–14- μm response. This instrument was piggy-backed on a payload designed to measure the CO_2 emission profiles in the Earth's atmosphere. The astronomical results from these experiments were limited to a possible detection of the Orion nebula and a measure of the upper limit to the diffuse mid-infrared cosmic background (Walker and Price 1970; Price and Walker 1971). These experiments, however, were valuable in demonstrating the necessity for cleaning and maintaining the payload free of particulate contamination (Price, Cuniff, and Walker 1976); even with the modest sensitivity of this instrument a dust particle can be seen out to at least 100 m in front of the sensor. The need for an accurate alignment procedure and a stable payload fixed to an external reference was also defined (Price *et al.* 1978).

Two new survey instruments were built by Hughes Aircraft Co. in 1970 with ARPA funds under the Air Force Space and Missile Systems Organization (SAMSO) management. These instruments, designated as the HISTAR sensors, were patterned after previously developed sensors for use in an exo-atmospheric environment. The doubly-folded $f/2.2$ Gregorian telescope had beryllium optics with a 16.5-cm aperture and an effective collecting area of about 150 cm^2 . The 1.2° cross scan field was covered by three linear staggered arrays of doped Ge detectors; each array contained eight $3/3 \times 10/5$ elements and was filtered to cover the 3–5- μm , 8–14- μm , and 16–24- μm spectral regions. The sensor was cooled from a supercritical helium reservoir. Seven experiments were flown on Aerobee 170 rockets from WSMR between April 1971 and December 1972. Most of the northern celestial sky was surveyed and the observations were compiled in catalog form by Walker and Price (1975).

Early in 1971 SAMSO conducted the first satellite-based infrared surveys. The initial endeavor used a liquid-neon-cooled telescope similar to the one used for the AFCRL proof-of-concept flights. The experiment was designed to take data until the neon ran out. Unfortunately, electrical cross talk from the spacecraft overwhelmed the sensor signals so only the brightest objects were detected. A more successful experiment was flown in the fall of 1971 using a HISTAR class instrument with a closed cycle cooler. Battery power requirements forced the sensor to raster scan parallel to the Earth's horizon with the result that the instrument was background limited by the off-axis radiation from the Earth. The area outside the solar avoidance limit, about 80% of the sky, was mapped several times in two infrared spectral bands before the mechanical cooler failed.

The HISTAR telescopes were refurbished in 1973, again under ARPA sponsorship, to improve the side lobe rejection, to incorporate a new focal plane with the more

sensitive doped silicon detectors, and to substitute a 24–30- μm filter for the one at 3–5 μm . Celestial coverage was extended to the Southern Hemisphere with three flights on Aerobee 200 rockets from Woomera, Australia in September 1974. The source detections from all the flights were compiled into the AFGL catalog (Price and Walker 1976) and its supplement (Price 1977). AFCRL was reorganized into the Air Force Geophysics Laboratory—AFGL—in 1976.

Various large-scale diffuse sources were subsequently extracted from the data, a complicated task as the high pass filtering in the signal processing electronics used to attenuate the low-frequency signals from side lobe radiation had to be deconvolved from the signals. Price, Murdock, and Marcotte (1980) report on 11- and 20- μm zodiacal emission along the ecliptic plane between 35° and 75° solar elongation. The diffuse mid-infrared emission within 5° of the galactic plane was mapped by Price and Marcotte (1980) and Price (1981). Higher-resolution maps were also published of the Cygnus region (Price, Marcotte, and Murdock 1982), the W3, W4, and W5 region (Thronson and Price 1982), and the galactic center (Little and Price 1985). A detailed description of the instrumentation, sensor performance, conduct of the experiments, and data reduction and analysis can be found in the report by Price and Marcotte (1980) and references therein.

A few comments are in order regarding the objectives of the AFGL survey, or any other survey, and the compromises required by the performance capabilities of the various components. Ideally, a survey should detect all sources brighter than a flux level set by the sensitivity of the instrument and reject all false or spurious signals. These spurious signals can arise from system noise, optical contamination, or transient sources such as man-made satellites and off-axis objects detected through instrumental glints. Obviously, a high degree of redundancy and survey sensitivity have to be balanced against the time available to cover the desired area. Survey sensitivity is a function of detector performance, collecting area of the optics, and the frequency bandwidth defined by the scan rate and detector width. The area surveyed is limited by the scan rate and time available to acquire data. The size and mass of the telescope and supporting payload limit the flight performance of the rocket and, thus, the time for data acquisition either directly for a probe or indirectly for a satellite with expendable cryogenics. A doubly folded Gregorian optical design was used for the Air Force survey telescopes despite the large central obscuration because of the weight advantage of its fast and compact system. It also allows a field stop to be placed at the intermediate focus for good side-lobe rejection.

The objective of the AFCRL survey was to measure the general, large-scale characteristics of the infrared emission from the celestial sphere about which little had been previously known. This placed a premium on cover-

ing as large an area as possible. Seven experiments were originally planned with the anticipation that five would be successful. The Aerobee 170 sounding rockets were able to fly the 200-kg payloads to altitudes of 155–165 km allowing 200 to 300 seconds of data acquisition. The HISTAR area scan rate was set to be $45 \text{ deg}^2 \text{ s}^{-1}$, the maximum consistent with telemetry restrictions at WSMR. Redundancy would be provided by the overlapping coverage from the different experiments, principally above 45° declination, and confirmation from ground-based observations.

Although more than half the sky was surveyed at least twice on overlapping flights, several factors compromised the re-scan confirmation. The inherent detector responses differed by as much as a factor of two in the array. The mid-infrared arrays were background limited during much of the data acquisition by radiation from the Earth and the payload through the side-lobe response of the telescope and the emission from the residual atmosphere above the payload. On subsequent experiments, Murdock and Price (1985) detected atmospheric emission above the payload to altitudes up to 280 km, much higher than the apogees of the HISTAR experiments. Inhomogeneities in this atmospheric emission created an additional source of spurious signals. Thus, although the average detection level in the AFGL catalog of Price and Walker was estimated to be about $2.5 \times 10^{-16} \text{ W cm}^{-2} \mu\text{m}^{-1}$ or 100 Jy ($\text{Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$) at 11 and $20 \mu\text{m}$ based on log (no. of sources) vs. log (flux) plot it was subsequently discovered that about 10% of the sources were spurious.

A reliable survey requires a high degree of self-confirmation while completeness can be assured by adopting a high intensity limit to insure source detection in confused areas and regions dominated by background noise. For example, the TMSS was limited to $K \leq 3$, some 2.5 times above the minimum detectable flux (Neugebauer and Leighton 1968, 1969; Hughes 1969) to assure survey completeness and to avoid source confusion in the galactic plane at the fainter fluxes. A reliable and complete AFGL catalog, say to 99% confidence level, would have been about five times smaller (Harris and Rowan-Robinson 1977; Grasdalen *et al.* 1983) with many of the more interesting sources deleted.

Rather than limiting access to the fainter and perhaps more interesting sources, all the detections consistent with the selection criteria were published and freely distributed. Confusion over the survey objectives and the caveats published with the catalog caused some initial reservation about the validity of the AFGL catalog contents (Low *et al.* 1976; Lebofsky *et al.* 1976; Gehrz and Hackwell 1976; Allen, Hyland, and Longmore 1976). Subsequent confidence was gained as the number of sources confirmed by ground-based observation increased (Kleinmann, Gillett, and Joyce 1981; Grasdalen

et al. 1983; Gosnell, Hudson, and Puetter 1979; Ney and Merrill 1980) and it was realized that many of the sources were extended, particularly those associated with H II regions (Kleinmann *et al.* 1979), and thus are strongly discriminated against by ground-based observing procedures.

The AFGL survey results indicate that the bright mid-infrared sky is dominated by cool objects; about half of the sources are late-type giant stars and the other half are objects with even lower color temperature ($T_c < 700 \text{ K}$). These low-temperature objects are either intrinsically cool or heavily reddened by localized extinction and are strongly concentrated to the galactic plane. Indeed, the circumstellar dust shell sources which are a significant constituent of the TMSS are among the brightest objects in the mid-infrared. The stellar visual and ultraviolet flux from these objects is absorbed by the circumstellar dust producing the large ($I - K$) indices while the warmed dust reradiates the energy in the mid-infrared. As a class, the circumstellar shell sources in the AFGL survey are much cooler than those in the TMSS. The optical depth of the dust shells surrounding carbon stars must be greater than that for M stars as the ratio of carbon stars to M stars among the AFGL objects is about twice that of the TMSS. Star formation and H II regions are intrinsically the brightest sources in the galaxy between 8 and $30 \mu\text{m}$ and therefore are prominent in the AFGL survey, constituting over half of the 20- and $27\text{-}\mu\text{m}$ sources. Bipolar nebulae, such as AFGL 618 and 2688, are among the unique objects found by the survey. These very luminous sources are thought to be preplanetary nebulae or proto-stellar sources embedded in dust which has disk-shaped geometry.

After the probe-borne surveys and the small-scale orbital experiments, the Air Force next planned to orbit the *Background Measurements Satellite* by the end of the 1970s. This satellite was to fly relatively large (36-cm primary) mechanically cooled infrared instruments to repeatedly survey the sky to faint flux levels and to measure the faint infrared emission from the upper layers ($> 80 \text{ km}$) of the Earth's atmosphere. Two prototype survey telescopes, designated H1 H1 STAR, and one earth limb sensor (ELS) were built. AFCRL was to fly the three prototype instruments on Aerobee 350 rockets with in-flight performances providing the basis for choosing the design to fly on the satellite. The first, and only, H1 H1 STAR flight was launched from WSMR in February 1974. An improperly seated fuel valve in the rocket reduced the peak altitude to $\sim 110 \text{ km}$ which allowed only 100 square degrees of the celestial sphere to be surveyed and these observations were badly contaminated by emission from the residual atmosphere above the payload.

The *Background Measurements Satellite* never materialized. Instead, additional probe-borne experiments were funded to measure specific backgrounds. Over 300

repeated scans of the sky near β Andromedae were made at the end of 1974 with a modified HISTAR sensor on an Aerobee 350 launched from WSMR, demonstrating that a space platform could be used for the coaddition advantage in sensitivity. Pelzmann (1978) also reported possible mid-infrared detections of several galaxies during this experiment. The Earth-Limb Experiment (ELE) was modified to include measurements of the absolute radiance from the zodiacal emission and six ecliptic plane crossings between $3^{\circ}5'$ and 23° Sun-centered elongation were made on an August 1976 flight (Murdock 1977).

The flight capabilities of the Aerobee 350 rocket, the largest research probe vehicle available in the mid 1970s, restricted the size, weight, and configuration of the payload which could be flown on these experiments. Thus, the HI HI STAR and ELE sensors could only sample small areas with limited viewing angles. Large area, sensitive infrared surveys on sounding rockets became possible when the surplus second stage of the Minute Man I was range qualified at WSMR as the ARIES vehicle. This motor is capable of lifting a 750 kg payload to a 380 km apogee which permits up to 500 seconds of data taking. The Rockwell HI HI STAR sensor, damaged on the 1974 flight during recovery, was refurbished and reconfigured for a payload designed for efficient and rapid survey scanning (Price, Murdock, and Shivanandan 1981).

A second instrument was developed around the 36-cm, all-beryllium optics built originally by the Perkin-Elmer Corporation as a technology demonstration for the study phase of the HI HI STAR contracts. This Far Infrared Sky Survey Experiment (FIRSSE), a collaboration between AFGL and NRL, had a five-color focal-plane array covering the spectral region from 8 to $120\ \mu\text{m}$. The instrument was conductively cooled from a superfluid helium reservoir which used a sintered-nickel porous plug for fluid containment.

The refurbished HI HI STAR instrument was flown in September 1982 from WSMR. About 30% of the sky was surveyed on that experiment with emphasis on the region around the galactic center out to 35° longitude. Earlier, in January of the same year, FIRSSE was also flown, the first successful large area survey of the sky at wavelengths longer than $30\ \mu\text{m}$. FIRSSE covered 21% of the sky in the general direction of the galactic anticenter. Price *et al.* (1983) published a list of the $100\text{-}\mu\text{m}$ sources brighter than 100 Jy detected on the FIRSSE flight and the Price, Murdock, and Shivanandan (1983) catalog lists all the far-infrared observations from this experiment. The mid-infrared observations from these two experiments were incorporated into the Revised AFGL Catalog (Price and Murdock 1983). This catalog is "complete" over the 47% of the sky covered by the two 1983 experiments to a flux level of about 85 Jy in spectral bands centered at 11, 20, and $27\ \mu\text{m}$.

Three other experiments obtained absolute narrow-

spectral-band radiometry on the diffuse infrared emission from the zodiacal dust in 15 bands between 2 and $30\ \mu\text{m}$ with a modest-sized ($80\ \text{cm}^2$ effective collecting area) off-axis telescope and relatively large, $5' \times 15'$, detectors (Murdock *et al.* 1980). The spectral bands had moderate resolutions, $0.1 < \Delta\lambda/\lambda < 0.4$, and were chosen to resolve possible silicate emission features in the dust. Flights in the summers of 1981 and 1982 sampled the zodiacal emission between 22° and 180° elongations and from -60° ecliptic latitude to the north ecliptic pole. A single plane crossing at 25° elongation was made with the same instrument and a different set of filters on an October 1983 flight.

The rocket-probe-borne measurements show that the infrared properties of the interplanetary dust are not simple functions of solar distance (Murdock and Price 1985). Hong and Um (1987) inverted the brightness integral for these observations of the thermal emission along the ecliptic plane and found that, contrary to what is generally assumed, no single power-law exponent represents the density of the zodiacal dust; the power-law exponent derived from the infrared brightness distribution varies with both wavelength and elongation. This result implies that the properties of the zodiacal dust are not spatially homogeneous and that the visual measurements of the zodiacal light sample a different mixture of particles than the infrared.

The zodiacal experiments also obtained spectroradiometry of the diffuse emission from the galactic plane at several longitudes; the highest signal-to-noise measurement is for a scan crossing the plane at a longitude of 36° . The spectral resolution is not high enough for unambiguous interpretation but the measurements are consistent with a gray-body emission of about 375 K with a deep $10\ \mu\text{m}$ silicate absorption and, possibly, band emission at $7.7 + 8.6\ \mu\text{m}$ and $11.3\ \mu\text{m}$ due to polycyclic aromatic hydrocarbons (Price *et al.* 1984; Price 1988).

With the successful completion of the IRAS survey, large area surveys from rocket probes became obsolete and AFGL has directed its efforts to more specialized experiments.

IV. Surveys from Satellite Platforms

In addition to the two mid-infrared surveys conducted by the Air Force in 1971, monitoring of long-period variable stars at $2.7\ \mu\text{m}$ from Air Force satellites has been reported by Marán *et al.* (1976, 1977). Additional survey detections of 896 sources within 10° of the celestial equator by these instruments were compiled into the "Equatorial Infrared Catalog" (Sweeney *et al.* 1977; Heimsheiner *et al.* 1978; Sweeney *et al.* 1978). Further processing (Nagy *et al.* 1979; Sweeney *et al.* 1979) increased the number of sources to 1278 and the survey completeness to 57.5% within the declination limits. The limiting magnitude of this survey is about 1.5 mag fainter than

the TMSS but the survey is incomplete within the area bounds.

A. The Infrared Astronomical Satellite

In 1974, the Netherlands funded a feasibility study for a long-wavelength infrared telescope on a satellite platform. About the same time NASA issued an announcement of opportunity for a satellite-based infrared survey. NASA combined the aspects of several proposals, formed a scientific working group from among the proposers for a mid- and far-infrared survey, and negotiated with the Dutch to consolidate experiments. A three-nation memorandum of agreement was signed dividing the responsibilities roughly along technical lines: the U.S. would build the survey instrument and provide the launch vehicle and launch support, the Dutch were to provide the spacecraft and auxiliary experiments in the focal plane, and the U.K. would be responsible for operational support and the preliminary analysis facility. The details of the *IRAS* survey instrumentation are given by Gillett *et al.* (1985) and the Dutch experiments by Wilde-
man, Beintema, and Wesselius (1983).

The *IRAS* telescope has a 60-cm diameter, $f/9.6$ Ritchey-Chretien optical bench made entirely of beryllium which is surrounded by a 750-liter superfluid helium cryostat. The large collecting area afforded by this two-mirror design over that of, say, a doubly folded Gregorian was at the expense of poorer side-lobe rejection. Redundant focal plane arrays in each of the four colors, 8–15 μm (Si:As detectors), 16–30 μm (Si:Sb), 40–80 μm and 80–120 μm (both Ge:Ga), provide confirmation of source detection within seconds as the instrument is scanned across the sky. A unique feature for the survey focal plane was individual field lenses for each detector to improve sensitivity and uniformity of response over the detector aperture. The Dutch auxiliary experiments include a low-resolution spectrometer with a resolution of $15 < \Delta\lambda/\lambda < 60$, and chopped photometer for near-diffraction limited mapping of small areas of 50 to 100 μm , and a short-wavelength channel for background statistics.

The *IRAS* electronics were dc coupled, permitting the large-scale diffuse components of the background to be measured. The stability and accuracy of the low-frequency measurements were improved by using matched pairs of self-heated JFETs in the preamplifiers (Low 1981) rather than low-temperature MOSFETs and reducing the bias on the detectors. The JFETs have significantly lower voltage noise and greater low-frequency stability than MOSFETs; the lower bias reduced (but did not eliminate) the multiple time constant and background related response enhancements common to low-background infrared photoconductors. These effects were significant for rocket-borne survey measurements using similar electronics at low frequencies (e.g., Zachor and Huppi 1981).

The *IRAS* survey was conducted over a ten-month period starting in early February 1983 and covered about 95% of the sky at least twice (Neugebauer *et al.* 1984). The survey was conducted with the telescope field held to within 30° of the radial vector of the satellite in its Sun synchronous orbit. Thus, the ecliptic coordinate system was the fundamental reference frame, with the majority of the scans at elongations between 70° and 101°. A small number of scans late in the survey included solar elongations between 60° and 120°. A complete description of the instrumentation along with the survey strategy and performance is given in Explanatory Supplement to the *IRAS* Catalogs and Atlases (1985).

In addition to the confirmation of source detection due to the redundancy in the focal plane, the survey strategy provided for rescan of a given area within hours, usually on the next orbit, and a subsequent resurvey months later. Thus, the premium was on reliability. The survey is complete over most of the sky to flux level of 0.4 Jy at 12 and 25 μm , 0.5 Jy at 60 μm , and 2.5 Jy at 100 μm (Rowan-Robinson *et al.* 1984). Although source confusion in high density areas such as the galactic plane and the Magellanic Clouds raise the flux completeness levels (Rowan-Robinson *et al.*, chap. VII of the *IRAS* Explanatory Supplement, 1985) fainter sources can be extracted by coadding the survey data in the regions which are not confused. Less complete is the small-scale structure catalog of Helou and Walker (1986) of 600 or so small (2'–8') sources and the 5000 plus stars in the Low-Resolution Spectral Atlas (Raimond, Beintema, and Olmon, chap. IX of the *IRAS* Explanatory Supplement, 1985).

About one-third of the data acquisition was spent on pointed observations. Many of these additional observations (AOs) consist of several scans centered on a selected source, the coadded images of which have been distributed (Young *et al.* 1985). Kleinman *et al.* (1986) extracted point sources from these fields and compiled them into a Serendipitous Survey Catalog which covers about 2.5% of the sky and is 3.5 to 7.7 times more sensitive than the sky survey.

The *IRAS* survey created a huge data base on the infrared celestial background, the analysis of which has barely begun. NASA has established the Infrared Processing and Analysis Center (IPAC) and a program for guest investigators to explore the full content of the data base. Beichman (1987) has written a review of current analysis of *IRAS* observations on solar system and galactic phenomena while Soifer, Houck, and Neugebauer (1987) review the *IRAS* extragalactic observations and subsequent analyses.

The sky is much more structured than previously thought. Most surprising was the discovery of the "infrared cirrus" (Low *et al.* 1984) so named for its filamentary structure. Gautier (1986) eloquently describes the appearance of the cirrus as having "long, spider-like

filaments, clumps, and long arching structures composed of small wisps, filaments, and clumps". The infrared cirrus appears to be emission from very small interstellar graphite and silicate grains (Draine and Anderson 1985) and/or band emission from carbon molecules such as polycyclic aromatic hydrocarbons (Puget, Leger, and Boulanger 1985) or hydrogenated amorphous carbon (Duley and Williams 1986).

Bands of enhanced zodiacal emission were discovered (Low *et al.* 1984) centered on the plane of symmetry of the zodiacal dust cloud and roughly 10° on both sides of it. These bands may be associated with the prominent Hirayama asteroid families, Eos and Themis (Dermott *et al.* 1985) and may have been formed by a single collision of two family members some 15–25 km in diameter several million years ago (Sykes and Greenberg 1986). Sykes *et al.* (1986, Sykes, Huntten, and Low 1986) have also discovered numerous dust trails in the zodiacal clouds, some of which can be associated with short-period comets. The *IRAS* Asteroid and Comet Survey (1986) catalogs over 7000 detections on known asteroids (Matson *et al.* 1986) and highly reliable detection on 24 comets (Walker, Matson, and Veeder 1986) including six discovered by *IRAS*. Many more of these objects probably lurk in the *IRAS* working survey data base.

Parameters for the galactic constituents can be derived from the large *IRAS* data base. Waters, Cote, and Auman (1987) and Cohen *et al.* (1987) derived the infrared photometric properties for normal stars as a function of $(B - V)$ index and spectral type, respectively. On the global scale, *IRAS* confirmed source-count extrapolations based on previous observations. Hacking *et al.* (1985) conclude that no new astrophysical objects were evident among the 271 bright 12- μm sources at galactic latitude (b) greater than 30° away from the plane. All but five of these objects were associated with previously cataloged sources, dominantly with those in the RAFGL catalog of Price and Murdock (1983). At fainter levels, the *IRAS* 12- and 25- μm source counts derived from the point-source catalog, the mini-survey (Rowan-Robinson *et al.* 1984) for the region $20^\circ \leq |b| \leq 40^\circ$ and at the north ecliptic pole (Hacking and Houck 1987) are consistent with the known constituents and distributions in the solar neighborhood. *IRAS* detections of circumstellar dust shell sources near the galactic center define the nuclear bulge at these wavelengths (Habing *et al.* 1985; Rowan-Robinson and Chester 1987).

The infrared cirrus and galaxies dominate the celestial background at the longer wavelengths. Chester (1986) estimates that almost half the 100 μm listing in *IRAS* point-source catalog are actually knots in the cirrus. About 25,000 galaxies were detected by *IRAS* only half of which were previously cataloged. In general the galaxies, mostly late-type spirals, are readily detected at 60 μm and are the dominant type of object at this wavelength away

from the galactic plane (Soifer, Houck, and Neugebauer 1987). Helou (1987) has analyzed the photometric properties of the normal galaxies.

B. Spacelab 2 Infrared Telescope

In August 1985 NASA flew a small infrared telescope on the Spacelab 2 Shuttle. This experiment had the dual objectives to monitor the infrared emission from shuttle contamination and to survey the sky at moderate resolution in five spectral bands between 4.5 and 120 μm . The ten-element photometer is located at the primary focus of a 15-cm diameter, off-axis aluminum primary mirror. Cooling from the 250-liter superfluid helium dewar is provided by vapor flow to the instrument across a rotary joint. Thus, the instrument could be raster scanned across the sky without moving the dewar. Single Si:Ga detectors in the 6.1–7.1- μm and 4.5–9.5- μm bands monitor the water-vapor contamination; the 8.5–14.4- μm band provides a cross reference with *IRAS* 12- μm band measurements and is sensitive to CO_2 ; three detectors each in the 16–30- μm band (Si:Sb) and 70–120- μm band (Ge:Ga) are comparable to *IRAS* 25- μm and 100- μm bands provide complete field of view coverage. Each of these detectors has a $1^\circ \times 0.6^\circ$ field of view, the center third of which is blocked with an occulting bar to modulate point sources into two characteristic peaks as the instrument is scanned. A single Si:Ga detector in a 2–3- μm band has an *N*-slit mask and is designed to be used as a stellar aspect sensor. Details of the instrument and mission are given by Koch *et al.* (1981).

This experiment indicated that the local background around the shuttle due to particulates, outgassing, and thruster firings is generally much greater in the infrared than the astrophysical background (Koch *et al.* 1987a). There were times, especially before sunrise when this background was relatively low, when meaningful observations could be made. Unfortunately, a piece of mylar on the sunshade came loose during the flight and was partially in the field of view. Thermal emission from the mylar saturated the mid-infrared detectors and produced low-frequency wandering of the background levels on the aspect detector and the long-wavelength band. Approximately 50% of the sky and 35% of the galactic plane was surveyed in the 4.5–9.5- μm band before the mylar problem occurred. Fortunately, the wandering baseline in the 2–3- μm and 77–115- μm bands can be filtered out. For these bands, data exist over 75% of the sky and galactic plane, including 85% of the region south of $\leq -30^\circ$ which is not covered by the TMSS. Melnick *et al.* (1987) and Koch *et al.* (1987b) published uncalibrated 2- μm maps of the galactic center and the first quadrant of the galaxy at a level roughly 10 times more sensitive than the Japanese balloon-borne surveys over the same regions at 2.4 μm . An uncalibrated 7- μm map of the Cygnus region was also published.

C. Surveys in the Near Future

The cosmic background explorer (COBE) is the only existing infrared survey instrument which NASA has manifested for flight. The objective of this experiment is to obtain high-precision photometric measurements of the large-scale isotropy and the spectrum of the cosmic background radiation. Mather (1982) described the instrumentation and outlined the mission. The diffuse infrared background experiment (DIRBE) is also pertinent to the present review. This is a multifilter radiometer using an off-axis Gregorian telescope contained in an IRAS-type dewar. Besides the IRAS survey bands the instrument includes near-infrared polarizers and spectral bands beyond 120 μm . However, the field of view is quite large, $1^\circ \times 1^\circ$, and the off-axis constraints are similar to that used for IRAS.

V. Conclusions

Applications of developing technology to infrared astronomy and the history of survey efforts have been traced. This includes the many innovative and pioneering efforts which, being partially successful, are seldom referenced even in review. Also in perspective is the support given by the U.S. Department of Defense, particularly the Air Force, to infrared astronomy and especially the surveys. Significant in this context is the development of low-background extrinsic silicon photoconductors funded almost entirely by the DoD.

The largest data base on celestial backgrounds is that obtained by IRAS and it will remain a source of fruitful analysis for years to come. However, this data base has its limitations in both scope and coverage. In particular, the wealth of detail on the zodiacal dust cloud is incomplete due to the limited range of solar elongations covered. Survey measurements as near to the Sun as feasible and near the antisolar region are needed to define the overall geometry of the cloud. The near-infrared zodiacal background has yet to be surveyed at high sensitivity; hopefully COBE will fill this deficiency but off-axis restrictions will limit the accessible elongations. Also, extensive spectral information is needed to determine the composition of the dust grains.

More sensitive and higher spatial resolution surveys would provide valuable information on the fine structure in the infrared cirrus, the faint end of the stellar luminosity function, and the contribution of normal and IR-bright galaxies to the background.

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